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Autonomous Mechanical Assembly on the Space Shuttle: An Overview

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ABSTRACT

The Space Shuttle will be equipped with a pair of 50 ft. manipulators used to handle payloads and to perform mechanical assembly operations. While current plans call for these manipulators to be operated by a human teleoperator, this article examines the possibility of using results from robotics and machine intelligence to automate this Shuttle assembly system. The major components of an autonomous mechanical assembly system are examined, along with the technology base upon which they depend. The state of the art in advanced automation is assessed in the Appendix.

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I. INTRODUCTION: THE SPACE SHUTTLE - A WORKSHOP IN SPACE

With the introduction of its Space Shuttle program NASA has initiated a new era in the utilization of space and space resources. Unlike all previous spacecraft, the Shuttle will act as a seed from which can blossom an entirely new class of challenging applications. Here we focus on a broad sub-class of these applications that involves handling and mechanical assembly. Construction of platforms, antennae, space stations, solar collectors, and other large structures in Earth orbit are examples. Each of these projects will require techniques for handling raw and fabricated materials, placing parts in precise translational and orientational relationships, and making the relationships permanent by fastening them in some way. In this article I examine the potential for application of techniques from advanced automation, robotics, and machine intelligence in making these assembly operations more automatic and less dependent on human intervention. As a result of employing these ideas, man's activities in space will become more productive, less expensive, and safer.

There are already plans to equip the Space Shuttle with first one, and then a pair of general purpose manipulators that can be used in solutions to these handling and assembly problems [33]. Working in a special cockpit, "payload specialists" will control the 50-ft. manipulators from a pair of joy-sticks and a number of other manipulanda, while observing progress through windows or closed circuit video. Other sensors mounted on the manipulators are being planned so that information can be displayed to the operator for interpretation and action [7].

These existing plans are for a teleoperator system that features man's active role in the feedback control loop. What we are investigating, however, is the replacement of man by automated computational machinery for many of the control, sensing, and sequencing operations required during these same assembly and handling operations. Applying techniques developed in advanced automation, robotics, and machine intelligence, and taking advantage of the computer's facility to deal with complicated sensing and control problems, it is possible to elevate man's role to that of an overseer who needs only to direct activities at an advanced level by issuing high order commands.

The basic idea here is to remove man from the role of a real-time sensory and control feedback element. This is done by replacing him with computational machinery, both hardware and software, that perform the required perceptual and control functions (see Fig. 1). In this way the human and computer each do what they do best: the human plans and makes high level decisions; the computer handles the myriad of details required by control of high order mechanical systems, optimizes energy consumption, ensures collision free trajectories, etc. While humans can be trained to accomplish many of these lower level tasks, we expect the fully automated manipulation system to out-perform the human teleoperator with respect to speed, dexterity, safety, and cost.

Though the distinction between a teleoperator and a robotic system need not be subtle, many features of the conceptual approach

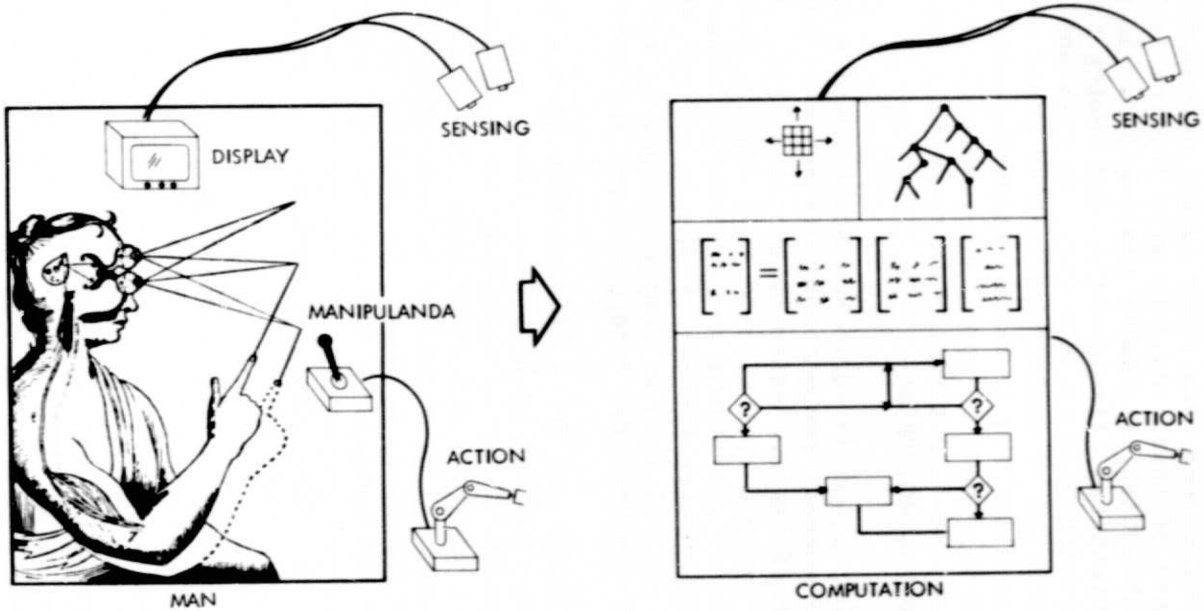

Figure 1. Replacement of Man with Computational Machinery

and hardware technologies found in these two disciplines are quite similar. It is not surprising, therefore, that one might find techniques from robotics combined with those from teleoperation in a single implementation. Such compromises may eventually prove useful, but the thesis pursued here is that under normal circumstances man should make no real-time control decisions for a manipulator based assembly system. Furthermore, we encourage the use of automated techniques for supervision and sequence execution, since they often involve rather routine bookkeeping and coordination procedures.

It is the purpose of this document to describe the major components of an automated mechanical assembly system, and to introduce general requirements for each component. It is folly to attempt specification of requirements without first obtaining a clear idea of what the system is to do. Since detailed plans do not yet exist for space assemblies, three fictional, but realistic, examples are presented in the next section to guide the discussion. Once the major functional components are introduced, we examine the specific technical elements that are necessary for successful assembly.

II. TASKS

Current plans call for the Shuttle manipulators to be used for a range of handling and assembly tasks. Payloads will be retrieved from storage and placed in orbit or retrieved from orbit and stored. Carefully pre-packaged devices will be deployed, perhaps by operating mechanisms once the device has been safely placed clear of the Shuttle bay. Still other tasks require a manipulator to perform a sequence of assembly operations that produce a needed structural component from a pre-packaged kit. Each task requires different resources.

We can describe the Shuttle automated assembly system as a pair of manipulators, a set of sensors, computational elements, a set of programmed algorithms, and perhaps a few special tools. All actions upon the environment are performed by the manipulators, and informative signals from the task environment are obtained from the various sensing elements. The manipulators are moved about so that raw materials and parts are transported, brought together, stacked, mated, fastened, and stored or unstored until the desired result is achieved.

In the discussion that follows it is assumed that the logical design of each task, (i.e., the sequence of events and type of operation performed during each event), is planned by human designers working on Earth during mission planning. Though looping and branching on sensed data are permitted, the major steps in an execution will proceed in a largely predetermined manner.

THREE REPRESENTATIVE EXAMPLE TASKS

In order to proceed with a concrete analysis, I introduce three example tasks that are representative of those to be performed using the Shuttle manipulators. The specific details of these tasks are not taken from actual plans, but are contrived to include a range of

generic features that such plans are expected to include. These examples serve as the focus for later discussion below:

TASK (A) Transfer a small, light satellite equipped with a grapple fixture from an orbit near the Space Shuttle to a storage place in the Shuttle bay. The initial orbit may include low velocity rotational and translational motion of the satellite relative to the Shuttle. These motions must be < .5 rad/sec and < 1 m/sec respectively [28]. This operation requires execution of the following sequence of steps:

1. Determine the motions of the payload relative to a Shuttle attached coordinate system.

2. The manipulator moves from a storage position in the Shuttle bay to the payload so that the end effector is in proper position relative to the payload. The accuracy of this positioning operation must be such that subsequent activation of the grasp mechanism does not produce undue movement of the payload. A sensor must provide information regarding the precise position and velocity of the grapple fixture on the payload.

3. The grapple fixture is activated.

4. The manipulator continues to track motion of the payload while an acceleration force is applied to bring the object to rest -- rotational and translational velocities must be nulled.

5. The manipulator and payload are then moved along a trajectory that avoids collision with objects in the bay, notably other stored items, to a vacant storage location.

6. The grapple mechanism is activated to release the payload. This must be done in a way that does not impart undesirable motion to the payload. It may also be necessary to fasten the payload to the bay in some way.

7. The manipulator is returned to a resting position.

Note that this scenario could be reversed in order to place a stored object into orbit. The requirements for this reverse process will probably not be the same, however.

TASK (B) Move a subassembly from the bay into position so that it can be attached to a larger assembly under construction outside of the Shuttle (see Fig. 2). Completion of this task requires the following actions:

1. The manipulator moves from its resting position to a suitable grasp point.

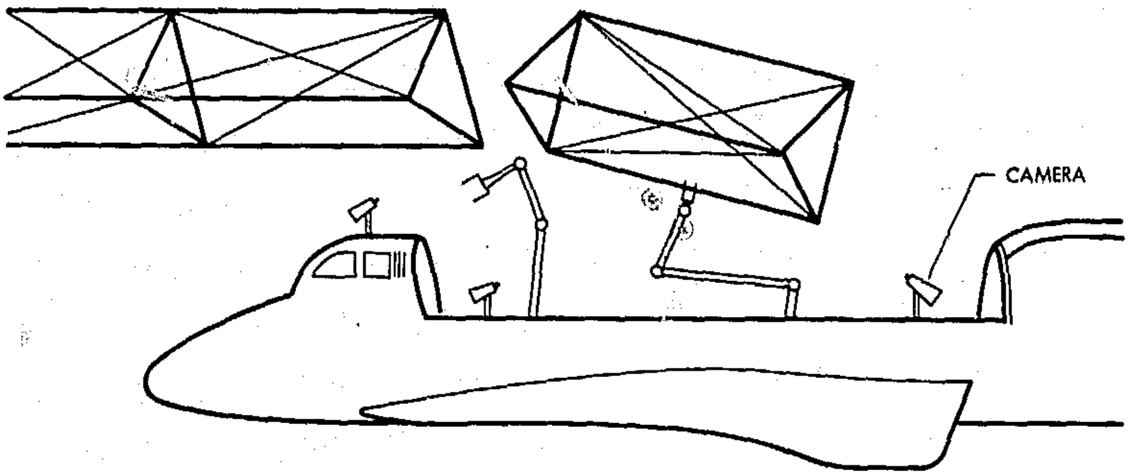

Figure 2. Mating and Fastening a Subassembly to a Larger Structure Under Construction

2. The gripper operates to grasp the subassembly.

3. The manipulator control algorithms are adjusted for the additional mass and moment connected to the gripper link.

4. A safe trajectory is chosen that moves the subassembly close to the goal position. Note that collisions of the subassembly with portions of the manipulator and with other obstacles in the environment must be avoided.

5. The subassembly is moved to mate with the main assembly at the three connection points simultaneously. During this operation it is essential to maintain precise stability of the Shuttle relative to the main assembly, or to measure relative movements precisely. Highly accurate manipulator control is also essential.

6. The second manipulator is used to fasten the subassembly to the main assembly at each point. This procedure may require a subsequence of operations, e.g.:

Move ARM 2 from rest position to storage location of fastening tool.
Move tool to first connection point.
Fasten.
Move tool to next connection point.
.
.
Deposit tool in storage.
Move ARM 2 to rest position.

Naturally, this operation would be much more complicated if extra parts were needed for fastening, or if ARM 2 could not reach all fasten points.

TASK (C) Select beam-like parts, tension support wires, and connectors from a specially prepared kit, and assemble them into the subelements of a larger structure. (See Fig. 2.) This activity takes place in the bay where parts are stored. Fixtures are available when necessary. (In what follows it is assumed that obstacle free trajectories are chosen.)

1. Determine precise location of first member.

2. Move manipulator from rest position to near grasp point of MEMBER 1 and grasp.

3. Place MEMBER 1 in vise fixture. (Connectors are pre-mounted on ends of MEMBER 1.)

4. Locate MEMBER 2 precisely and grasp.

5. Move MEMBER 2 into position and mate with MEMBER 1. This may involve alignment and insertion procedures.

6. Fasten MEMBER 1 and MEMBER 2 using connector. At this point fixturing is needed to provide structural support for the unfinished subassembly since sufficient structural elements are not yet in place.

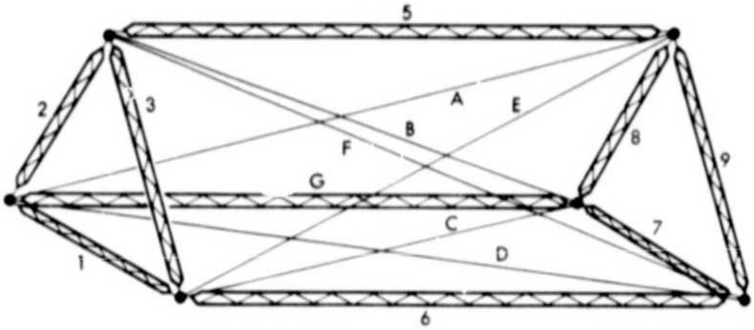

Figure 3. Example of Subassembly that is Constructed in the Shuttle Bay

7. Inspect progress and check for errors.

8. Fetch and position MEMBER 3.

9. Fasten MEMBER 3 to MEMBER 1 and MEMBER 2. Because MEMBER 3 will be mated at both ends, movement of MEMBERS 1 and 2 may be required. This will depend on the exact nature of the connector mechanism.

10. Inspect structure for correct shape and for strength.

11. Fetch, position, and attach MEMBER 4.

12.-18. Locate, grasp, and install Members 4, 5, 6, 7, 8, and 9. Perform an inspection after each operation.

19. Attach one end of tension support CABLE A to connector at junction of MEMBERS 1, 2, and 4.

20. Attach the other end of CABLE A to connector at intersection of MEMBERS 5, 8, and 9. The cable must be stretched to prescribed tension before fastening. An iterative procedure that repeatedly tightens each cable may be required. This stretch-measure tension-fasten operation should probably be done with a special tool that is positioned by the manipulator.

21.-25. Install support cables B, C, D, E, F.

26. Inspect entire structure.

In these examples no mention has been made of the manipulator control mechanisms, nor the method of sensing the various conditions upon which decisions are made or control is achieved. The idea was to describe these tasks without regard to the method of solution. For example, the "precise positioning" called for in certain assembly steps might in some cases be achieved through the use of sensory information, while for others a priori information will be adequate. Of course we have restricted ourselves to the Space Shuttle manipulation scenario in which manipulators are used to produce all motions and extra vehicular activity is not considered.

The entire operation theoretically could have happened under control of a teleoperator using only the operator's direct sensing and perceptual abilities. We are interested in discussing another alternative, where the operator takes little or no part in the activity once the decision is made to start a particular sequence. In this case computational machinery is responsible for determining the proper next step in a sequence, perceiving the state of the environment through sensors, controlling manipulator motions, and measuring the successful execution of each operation.

At the present time there are no detailed plans for many of the manipulation applications to which the Shuttle may be applied. The mechanical designs for grapple fixtures, beam connection fittings, and even the gross features of structures await further development and planning. This lack of specification has both positive and negative effects

on the present task of determining technology requirements for automated manipulation. Our efforts suffer from the difficulty of not knowing the precise nature of the assembly design: What motions are required? What will be the tolerances? Double insertions? Gripper requirements? At the same time we have the opportunity to influence the ultimate designs in each of these areas (connectors, motions, tolerances), in such a way that our job will be made easier. The current underspecification opens the way to considering assembly problems and the results of laboratory experience before the mechanical designs are complete.

GENERIC ASSEMBLY OPERATIONS

Using the example tasks as a guide, we can divide the components of the assembly process into five generic operations: transfer, grasping, mating, fastening, and inspection:

Transfer

During transfer the manipulator hand and its contents are transported from one location in the assembly area to another. In many cases the starting or ending point for a transfer motion are run-time variables since they may be specified from sensory information rather than from advanced planning knowledge. When manipulated objects are in motion, initial or final manipulator velocities may also be run-time variables. Therefore, initial and final "state" of the manipulator are the basic parameters of a transfer motion.

Since transfer is characterized by large manipulator motions, an important requirement is that no unexpected collisions take place among the manipulators, the manipulated objects, and other parts of the Shuttle. Overall speed and smoothness may also be important, as well as other trajectory attributes.

For examples of transfer see task steps A-2, A-5, B-1, B-5, C-5, C-9.

Grasping

Grasping is the operation of temporarily attaching a manipulated object to the end of the manipulator. Before grasping can occur, the manipulator hand must be placed in precise position relative to the object. If the object is moving the hand must also move to maintain the correct juxtaposition of surfaces. Then a mechanism is activated which performs the actual attachment.

Sensors that help to achieve the required relative positioning are important to grasping, as is consideration of suitable grasping surfaces on the manipulated object. Availability of good grasping surfaces can relax requirements on positional accuracy and provide a more rigid attachment. Grapple fixtures, mechanical devices attached to the manipulated object, are designed to provide ideal grasping surfaces, often yielding relaxed positioning requirements, rigid attachment, and facilitated sensory processing.

For examples of grasping see task steps A-3, A-6, B-2, C-2, C-12.

Mating

Perhaps the most basic step in mechanical assembly is the mating operation. By executing "controlled collisions", points, edges, and surfaces on two or more objects are brought into contact in a prescribed manner. Within the category of mating, insertion forms the largest and most typical subclass. Mating operations generally found in the factory require 0.1 to 1.0 mil accuracy. Since this is well below normal human visual resolution and the hands obscure vision during manipulation, force sensing plays a crucial role.

For examples of mating see task steps B-5, C-3, C-10.

Fastening

Fastening is the process of making a mate permanent. The basic goal is to maintain permanent contact between two or more objects. Typical of the fastening operation is the fastener -- an additional part or parts that are introduced to make the fastening possible. Transfer, grasping, mating, and inspection often play major roles in fastening.

For examples of fastening see task steps B-6, C-6, C-10, C-21.

Inspection

By obtaining sensory information from the task environment, the success of a previous operation is tested. Optical, mechanical, and electrical sensors may be employed. However, inspection is often more than just a passive sensory process -- the response to a stimulus is often required (e.g. checking the tightness of a cable). To obtain robust and reliable performance, inspections must be performed continuously throughout an assembly.

If the assembly operations required for the three examples, tasks A, B, and C, are examined in terms of required resources (types and numbers of sensors, amount of sensory processing, precision of movements required, and special fixturing), we can summarize our findings, as shown in Table 1. Each of the situations depicted on the left exemplifies a handling task that needs lower accuracy, fewer sensors, less control computation, or reduced demand on special purpose hardware. Tasks involving those on the right place higher demands on the system.

Table 1. Task variables that affect requirements

grasp using fixture	<==>	free grasp
compact object	<==>	elongated object
low mass object	<==>	heavy object
object stationary during grasp	<==>	object moving
single point mating contact	<==>	multipoint mating
parts attached to Shuttle	<==>	floating parts
slow movement	<==>	fast movement
activity inside bay	<==>	outside bay
no fixturing	<==>	fixturing required
one manipulator	<==>	multiple manipulators

TASK PROBLEMS PECULIAR TO NASA

Most of the technology and conceptual approach described in this article closely parallel attempts to automate mechanical assembly and handling operations in Earth-bound industry. In taking this approach we benefit from extensive experience derived in dozens of laboratories and factories over the last decade. In extending this technology to space, however, we encounter new problems for which no experience now exists.

First consider the large dimensions. Virtually every successful use of manipulators on Earth has involved handling of rather compact objects in a restricted region of space (i.e. the work station) [8,14,21, 25,31,35,49,51]. No large moments are generated and precision is only required near the hand. Note the following difficulties that arise when handling long beams of the type found in every plan for large space structures:

- Small errors in angular positioning of the manipulator wrist result in very large errors in the endpoint positions of the workpiece. These endpoints are the very spots where part mating and connection must take place.

- Solid gripping is made more difficult by large moments in the gripping plane. Resulting slippage is magnified at the beam endpoints.

- Beams often require precision placement of both ends simultaneously [6]. A single visual sensing system cannot, in general, monitor activity at both ends of the beam at the same time.

- Two-handed manipulation may minimize certain of these problems, but this is essentially a new technology [26].

Though certain advantages are expected from manipulating in a zero gravity environment (0-g), (ie. primarily an increased load carrying capacity), there will also be complications. Since nothing can be left "sitting on the workbench", large demands will be placed on fixturing, parts holders, and other restraint mechanisms. The manipulation system will be responsible for maintaining contact between mated parts until a fastening procedure is performed, since there are no natural forces performing this function. Perhaps the most troublesome fact is that accurate simulation of a 0-g environment is not possible on Earth. This means that the first few assembly experiments actually conducted in space will be very risky learning ventures.

Achieving economy of energy consumption during a manipulation procedure is another factor of little concern in the factory or laboratory, but of substantial importance in space. Task strategies and manipulator trajectories should be selected to minimize energy usage. Though a wealth of literature exists in the general area of optimal control, few attempts have been made to apply these techniques to multi-joint, serial link manipulator control [23, 43].

III. REQUIRED TECHNOLOGY

To understand how these tasks can be accomplished in the manner indicated, it will be useful to describe briefly the major components of an automated assembly system, and the technological constituents of each. The automated assembly system is composed of four major elements: A supervisory element, an element that perceives the state of the environment, an element that affects the environment, and the assembly task itself (see Fig. 4).

Research in machine intelligence and robotics has contributed extensively to our understanding of these four areas during the past decade. As a result many of the techniques needed for Shuttle automation are already available in the laboratory and some have been accepted in the factory; they need only be refined and adapted to the special rigors of space usage to be useful. Other areas are less well developed and will require additional basic research, experimentation, and new technology, in addition to space qualification. The Appendix gives a brief assessment of the state of the art.

In the following sections I will describe how technical developments from each of these four areas contribute to automation of mechanical assembly procedures. I concentrate on specific questions for automation of the Space Shuttle manipulation system: What technology is needed? What technology is well developed? What looks ripe for development? What problems have no solution in sight? Here again, specific application tasks are quite important and the three example scenarios are referenced.

AUTOMATED SUPERVISOR

When a teleoperator performs an assembly operation the manipulator executes a sequence of actions that result in achievement of some goal. During execution, the human specifies which action is taken next in the sequence, his decision often depending on the outcome of a previous step. The division of function between the manipulator and the human is often called supervisory control. For a robot, a similar supervisory function is needed, but it is no longer performed by a human. Instead, an automated supervisory computer program invokes the sequence of actions, evaluates sensory information, makes its own decisions, and inspects its own work [36, 40, 17].

One important function of this supervisory software is to permit efficient communication between humans and the automated system. Telling a robot what one wants it to do can be a difficult job. We liken the human telling the supervisor what the robot should do, to a plant manager telling a foreman what his group is to do. A special language is required that incorporates a vocabulary rich enough to describe what needs to be done, but with as little conversation as is reasonable. Clearly, a more responsive and intelligent foreman makes the manager's job easier and more pleasant.

This process of interaction between the human and assembly system will take two forms. During mission planning, technicians will teach the system how to perform a particular assembly. First the logical

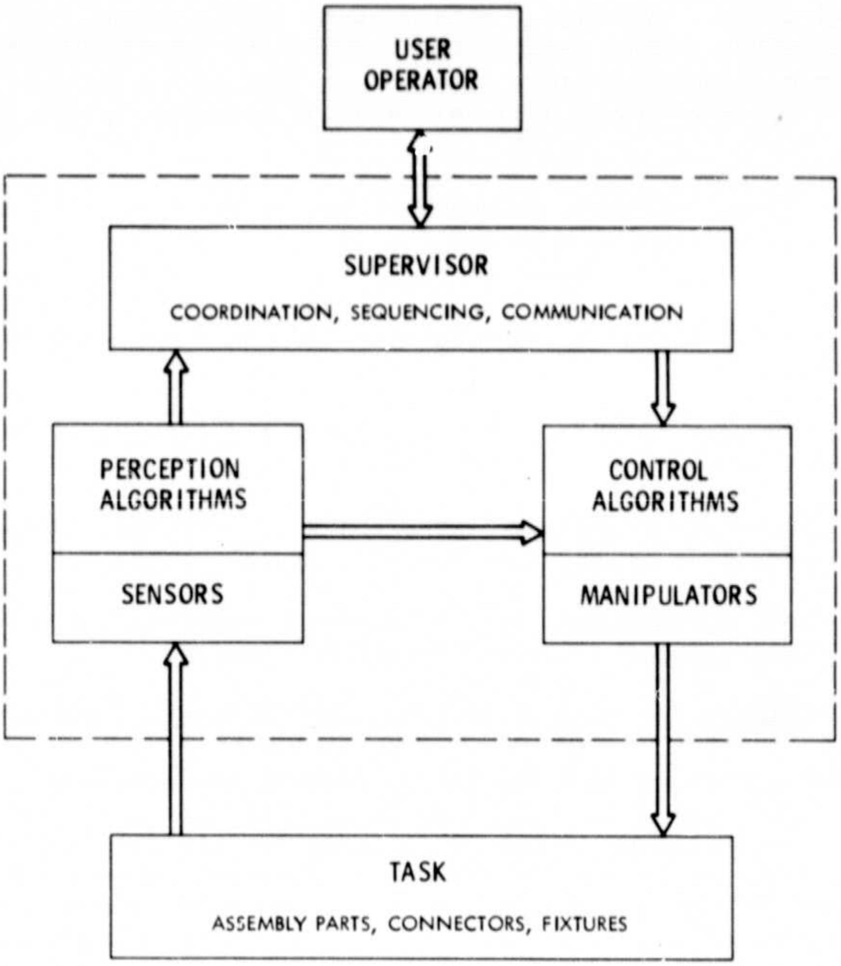

Figure 4. Major Components of an Automated Assembly System

sequence of actions, (grasps, transfers, insertions, inspections, etc.) are specified in symbolic form. Then data are trained that specify the precise details of part and fixture locations, and important dimensions. Many powerful techniques already exist for this type of instruction, though additional consideration may be required for the Shuttle application, since training will take place in 1-g and actual performance takes place in 0-g.

The other form of interaction takes place during a mission. Here the assembly supervisor keeps the operator informed of the system's operational status, especially when unusual events occur. It also provides a facility that permits the operator to intervene with changes to the original assembly plan, or modifications to a plan gone wrong. This option of interacting with the behaving assembly system is very important.

The other important function of the supervisor is to provide coordination among system components. Since an assembly system is typically composed of a number of subsystems, both hardware and software, achieving any result requires careful orchestration. Even telling such a system to STOP will often require issuing a detailed set of instructions.

An assembly supervisor for the Space Shuttle should perform the following combination of functions:

- Detailed information about the status of the system is made readily available in an easily understood form.

- Self documenting, easy to generate commands can be given in a teaching mode and during run time.

- Changes can be made to previously determined plans.

Strong support for interaction between the operator and the automated supervisor are required to obtain the best performance from both the man and machine. Current teleoperator techniques (especially manipulanda) do not permit intimate human-computer interaction, because the operator is busy with special purpose joysticks, knobs, and buttons. A keyboard permits a more general class of commands, though analog instruction is difficult.

Special safety features will be required for a Shuttle supervisory system. These safety features are generally unnecessary and often undesirable in the laboratory, and will, therefore, require special attention.

When confronted with unfamiliar assembly tasks, humans are reliably able to generate successful assembly plans that specify ordered sequences of operations, effective inspection procedures, and error recovery strategies. In this section we have described an automated assembly supervisor that includes none of these abilities. All planning, sequence generation, and error recovery techniques will be worked out in advance and made available to the robotic system by humans. Though automated

planning systems have received substantial research attention in the past ten years, [15, 16, 30, 31, 42, 49], the remaining problems are difficult and the field is still rather immature. Other problem areas may find suitable applications for such planning systems before 1990, but automated mechanical assembly in space will not.

MANIPULATOR CONTROL

In order to allow a manipulator to operate independently of direct human control, it is necessary for motions of the manipulator to be controlled by a computing system. Such a system must have a trajectory planner that satisfies the goals of each movement without undesired collisions and a control program that moves the manipulators along planned trajectories. Trajectories must ensure collision-free transit, and energy minimization may be desirable. The controller must compensate for certain of the dynamic properties of the manipulator including those changed by grasped objects.

Automatic trajectory control is probably the single most useful, best understood, and most easily implemented technique that can be applied to the Shuttle assembly system. A wide range of functions can be performed using a trajectory controller: a human operator can invoke an automatic movement to a much used position. The operator can routinely specify movements in terms of desired position, letting the system determine and execute the movements. Or the system can have a sequence of operations to perform that invoke movements through such a trajectory control system. The entire range of autonomy, from advanced teleoperator, to the full fledged robot will make use of the trajectory controller. Therefore its development is central to any automation plan.

A benefit of automatic trajectory generation is the opportunity to use energy-efficient movements. Because the Shuttle manipulator is so large, and payloads may approach 60,000 lbs-mass, large energy savings are possible if operators do not "jocky" the payloads about. An automated trajectory planner can use standard techniques to generate energy minimizing manipulator trajectories.

Obtaining solutions to minimization criteria during an assembly may not be feasible due to computational limitations, but precalculated results could be useful for certain sets of movements. There may also be general "modes" of operation or regimes that yield lower cost motions on the average. In any mode where joystick commands do not directly determine the exact path of manipulator movement there is room for automatic reductions in energy usage. Permitting specification of via points and goal end-points would allow incorporation of the human's ability to choose obstacle-free paths, while including some degree of energy optimization.

Most manipulators used for Earth applications employ simple servos closed separately about each manipulator joint [24]. Changing moments of inertia, inertial coupling between joints, velocity interaction terms, and linkage flexibility are ignored by these controllers, while feedback is used to eliminate the adverse affects of all factors. The resulting level of performance is adequate for many applications,

especially where arm velocities are low enough so that centrifugal and Coriolis forces are of little consequence. In other cases accuracy requirements are sufficiently low so that more sophisticated control is not needed. Under other circumstances, however, simple servo controllers yield sluggish and insufficiently precise performance. It is notable that at least one large reach, large mass industrial manipulator must be operated below maximum velocity (determined by actuator strength) in order to meet stability requirements.

For control of the Shuttle manipulator there are a number of factors recommending compensation for some of these dynamic terms. Its size is one obvious factor. Large moment arms produce strong inertial coupling forces that perturb operation. In many instances the precision required during grasping or mating operations will be high enough to make compensation essential. Finally, plans to handle very large payloads will require a more comprehensive compensation algorithm, since critically damped loops may depart markedly from desired performance when the mass of the hand changes by several orders of magnitude.

This last problem has strong implications for the teleoperator. Due to the long time constants associated with large masses, predictive corrections will be required over intervals of many tens of seconds. Though training can compensate for the difficulty of performing in this circumstance, safety considerations will demand very slow operation. Using automatic techniques, the throughput of the system can be greatly enhanced while maintaining adequate safety margins.

When a manipulator is moved about it is desirable to prevent it from unexpectedly colliding with other objects in the environment. There are two general schemes for protecting against such inadvertent incidents. The most general approach is for a geometric model of the manipulator's environment to be available to the trajectory planning system [30]. In this model is represented each potential obstacle and the manipulator itself. In order to choose a collision free path a computing element checks for intersection of the manipulator body with the space occupied by each of the potential obstacles. Though a number of heuristics exist for simplifying this procedure, it usually requires an unacceptable amount of computer time and memory to be employed in its most general form.

Another solution is to plan the environment so that safe passage is ensured if certain rules are followed. Restricting all objects to rest on the work surface, and causing all trajectories to move "up", "over", and "down" is such an approach. Intermediate between these approaches are those that only model each obstacle roughly, using some sort of convenient envelope, and then use a restricted set of trajectories designed to avoid these envelopes [29].

It may also be possible to devise a sensory system that can detect impending collisions early enough during a motion to avoid forceful impacts. Proximity sensors come to mind for such an approach.

SENSING

Sensors and sensory processing give an automated system information that can be used to compensate for uncertainties in the environment and uncertainties in the automated system itself. Perfectly precise manipulators acting in a perfectly ordered environment do not need sensors, especially if 100% reliable operation is not required. Indeed, a number of industrial robotic applications function quite respectably in a virtually open loop manner. Yet the cost of such operation, in terms of precision hardware, constraints on organization of the environment, lack of flexibility, and the impact of failures, can be quite high.

In terms of the Shuttle manipulation problem there are three basic reasons why sensing is required:

- Not every aspect of the environment will be under NASA's control during manipulation operations. The scenario task of satellite recovery is a good example; here, the exact position and movement of the payload is not available from a priori knowledge. It must be obtained by examining the environment with sensors throughout the manipulation period.

- Manipulators and accessory equipment of sufficient precision to obviate the need for closed loop operation[1] are too heavy, cumbersome, and lack the versatility needed to economically fly on a spacecraft.

- Robust and reliable performance will be of paramount importance during Shuttle manipulation procedures. Only through effective sensing can the small variations that cause failures be detected and accommodated, and in this way only can the failures themselves be detected once they occur.

It must be made clear that transduction and communication play only preliminary roles in effective sensing. Once sensory data are made available they must be processed to yield useful information, and then useful results. It is this computational factor, often ignored or slighted, that makes effective operation difficult to achieve.

There are five different sensors falling into two categories that are most useful for robotics applications. The first category of sensor, "terminal sensors", are carried on the manipulator hand, or end effector. They provide data about the relationship between the environment and the business end of the arm.

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[1]The manipulator has internal position and velocity sensors that are always used in controlling movements. But control is not always closed through the environment.

Force sensing gives the manipulation system information about the mechanical coupling that occurs when the hand comes into contact with objects. Typical force sensors incorporate strain gauges mounted on the fingers of a gripping device, or in the arm's wrist. They indirectly monitor forces and torques by measuring deformation of known mechanical elements. The resulting information can be used directly in the feedback loop of a manipulator control algorithm [26, 32, 38, 50], or in generating knowledge about the manipulative state [25, 44].

Touch sensors are special case force sensors that indicate contact of the hand with the work environment. Additional information about the location and pattern of contact is also often provided [20]. These discrete data can be used to detect obstacles, verify the success of a grasping action, or detect slippage between the hand and a grasped object.

Proximity sensors tell the manipulation system when objects are in the vicinity of the sensor. These devices can be used to avoid obstacles and to precisely locate objects for grasping, or other forms of handling [5]. A prototype set of proximity sensors have been used in a teleoperator mode with the JSC training arm. Preliminary reports show them to be quite effective in aiding a passively cooperative grappling operation [7].

The second category of sensing system is based on optical imaging, and can be loosely called computer vision. Here the overall environment of the manipulation system can be monitored for a variety of factors. As with the force sensor, information from a computer vision system can be used directly in low level control algorithms [9, 19, 40], or in acquiring knowledge about the task environment so that decisions can be made [22].

Many different basic approaches exist for computer vision, encompassing a variety of hardware configurations and algorithmic techniques [11, 52]. For the Shuttle we emphasize only two sets of techniques:

- raster scan video devices that generate two dimensional digitized grey-level images at normal video rates, and
- laser ranging devices that generate depth maps of objects in the environment.

Once again I emphasize that imaging, transduction, and communication of image data comprise only minor components of the computer vision challenge. Powerful computational elements are required to make useful perceptions upon image data in an acceptable amount of time. In most cases there are only two alternative means of providing useful real-time service from a vision system: 1) use extremely simple algorithms that execute with sufficient speed on existing general purpose computers, 2) implement more demanding algorithms with special purpose high speed computational hardware.

Solutions to the general vision problem, i.e., where objects, backgrounds, lighting conditions, and object motions are unconstrained,

do not now exist (except in biological form). By labeling objects, constraining the background, manipulating lighting conditions, and using a priori knowledge about object motion we obtain a tool of unparalleled usefulness. Indeed, the fact that the user of a teleoperator relies heavily upon his visual sense is a good indication of its importance to effective manipulation.

In addition to using vision for direct servoing of the manipulators and for allowing freedom in the placement and orientation of parts, vision can be used in situations where a priori knowledge of a task parameter is not available. Position and motion of the satellite in Task A, discussed earlier, is an example. Vision can also contribute to the Shuttle's ability to maintain position and orientation relative to other spacecraft, platforms, or structures. When manipulating with respect to such structures, residual errors in Shuttle stability can be detected and their effects nulled by modifying manipulator control signals.

The potential for computer vision in automated assembly and other application areas in space is enormous and exciting, but should not be cataloged here. For more extensive, but general accounts see Winston's text [52].

MECHANICAL CONSIDERATIONS

A long term goal of robotics research has been to develop machines that have the flexibility to perform all the functions required in a particular domain, without resorting to the use of too many special tools, fixtures, or other paraphernelia. While the costs of fixed automation on Earth can only be justified for very high volume production, the cost of versatile machines can be amortized over production of a wide variety of low volume products. Similar arguments apply to automated mechanical assembly operations performed in space. Versatility is desirable for space applications since a wide variety of relatively low volume tasks are to be performed, and the costs of putting additional hardware into orbit are high.

Three questions are of importance to these versatility issues: 1) Where can the manipulators reach and with what orientations? 2) What set of grippers and special tools are needed to perform all necessary functions? 3) How much special purpose fixturing and jigging is required? Naturally, little can be decided without detailed information about the task set, but we can make some general preliminary observations.

It is suspected that for all but the most trivial tasks two manipulators are an absolute minimum. Working through example Task B one sees that a substantial amount of fixturing is required to hold subassemblies in position while additional parts are added. Some of these fixtures could be replaced with additional, smaller manipulators located in the bay area. If large packages can be precisely positioned only when handled by two arms, additional devices will be required to perform fastening operations.

Though conventional wisdom recommends the use of manipulators having six degrees of freedom, this should be considered a lower limit. Six jointed arms permit the hand to be positioned and oriented arbitrarily within the work space.[2] However, the space occupied by the body of the manipulator is not so unconstrained. Only manipulators having a so-called redundant design, i.e., more than six joints and links, can reach points in space with a range of configurations (e.g., freedom to position the elbow away from obstacles). When the manipulators are used to reach points within a frame-like structure, or any cluttered environment, this ability to select from sets of arm configurations will be quite valuable. These arguments are of little immediate relevance here since the manipulators currently planned for the Shuttle are not redundant designs [13].

An ideal manipulator system would use a single very dexterous, very sensitive hand to perform all manipulative tasks. However, end effectors of sufficiently sophisticated design do not currently exist; most manipulators use mechanisms having just two or three very simple "fingers", each with a single articulation.

One way to compromise the lack of versatility demonstrated by today's grippers with the demanding characteristics and requirements of an assembly task is to use sets of interchangeable, special purpose end effectors. This technique permits each end effector to be of a very special-purpose design while the overall assembly system retains its versatility. This concession to specially designed hands is not, however, made easily: 1) A means of changing end effectors is required -- a requirement complicated by the presence of sensors and their electrical and possibly optical connections to computational equipment; and, 2) a great deal of time may be required for changing grippers [34]. Unfortunately grippers, sensors, and control mechanisms sufficiently versatile to obviate the need for this strategy do not yet exist.

As advanced gripper designs include more and more sensing elements, the problems of signal communication increase. Most present manipulators use a separate set of wires for each hand mounted sensory system. This results in difficult reliability problems when the wires are routed to processing electronics through some five or six mechanical articulations. Some sort of unified sensory communications system should be developed, possibly making use of custom designed integrated circuits and a single high bandwidth channel.

Almost every point and issue in this section on mechanical considerations applies equally well to the teleoperator concept as to the automated system. Workspace analysis, gripper design, and fixturing are task related problems that are indifferent to the implementation media of the controller -- silicon or protoplasm.

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[2]This claim of generality for the 6 degree-of-freedom manipulator suffers from circularity, since the work space is usually defined in terms of the kinematic properties of the manipulator.

COMPUTATION

From the foregoing discussion it should be clear that computation plays a crucial role in almost every aspect of an autonomous assembly system. Trajectory control, obstacle avoidance, force sensing, energy minimization, task planning, sequencing, and computer vision are problems that might have trivial solutions were it not for unusually demanding computational requirements. Any attempt to automate the Space Shuttle's assembly system must allow for a sizeable investment in machinery that can satisfy these requirements.

Recent advances in computer electronics have produced a host of new components (processors, memories, logic elements, etc.), that are faster, more powerful, consume less energy, cost less, and are lighter than ever before. The use of custom designed large scale integrated circuits (LSI) can extend these economies even further. With these advances the problem of providing the Shuttle with adequate computational facilities for autonomous operation is more one of algorithm and software development than of electrical or computer engineering, though certain system integration issues are still important.

The computers required to perform computational functions for sensing, control, and supervision fall into two basic categories: general purpose stored program machines and special purpose hard-wired processors. General purpose machines are needed for functions that depend on a variety of sequential operations, especially when branching is common. They can be used when real-time demands are only moderate, or when aided by other computational devices. Special purpose processors can be very fast, so they are used where algorithms are time-critical. The speed of the special processor is obtained at the expense of flexibility -- they are generally restricted to implementation of algorithms that are very regular and do not depend on a large variety or large number of sequential steps.

Though no precise prediction can be made here, the following is a brief account of computational requirements for automation of the Shuttle:

- An automated supervisor will require a moderately large general purpose machine to support sequencing, safety monitoring, and interaction with the user.

- Manipulator control can best be achieved by combining a general purpose computer, used for trajectory generation, energy minimization and obstacle avoidance, with special hardware that actually controls the manipulator.

- Computer vision in particular and sensing in general has requirements that also favor combined use of a general purpose computer along with dedicated equipment. A sequential machine is needed to perform recognition functions at an intermediate level on data that are pre-processed by a set of special purpose processors.

IV. SUMMARY

The main thesis of this article is that the Shuttle manipulators can and should be automated so that humans need only play a guiding role in handling payloads and assembling structures in space. The four cornerstones of an automated mechanical assembly system were described -- automated supervision, manipulator control, sensing, and the mechanical characteristics of manipulator and the task -- with an introductory analysis of important development areas. These development areas include:

- Highly interactive assembly supervisors that coordinate subprocesses, permit the user to easily instruct the system, and allow control with safety during run-time.
- High precision manipulator controllers that conserve energy and avoid obstacles.
- Use of sensory information in situations that lack a priori description, for control during mating and fastening, and for inspection.
- Redundant manipulator designs, dexterous grippers, and communication with hand mounted sensors.

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APPENDIX

STATE OF THE AUTOMATED ASSEMBLY ART

Each of the four major technology areas of automated mechanical assembly and some of the necessary components have been discussed in the text. We are left with the question, "Which of these components are available, and which require more research and development to be useful?" None of these technologies has been flight qualified, though a number have found their way into industrial applications.

In this Appendix, each technological component is listed with a code that roughly indicates its state of advancement:

Factory	The technique is being used successfully in the factory.
Lab	Successful use in the laboratory.
Experimental	The problem is receiving experimental attention in the laboratory, but no working prototypes yet exist.
0	An unexplored problem.
-	The problem lacks signs of near-term solution.
?	No data.

AUTOMATED ASSEMBLY SUPERVISION

Methods for off-line training of logic data and trajectories	Factory
Sensory based decisions easily specified to supervisor.	Lab, Experimental
Powerful tools for debugging and modifying assembly plans.	Lab
Coordination of hardware and software subprocesses.	Lab, Factory
Methods for insuring safe operation.	0
Automatic assembly plan generation.	Experimental, -

MANIPULATOR CONTROL

Servos

PID servos - Each joint is controlled separately. No dynamic compensation.	Factory
Paul servo - Each joint is controlled separately. Corrections for gravity and changing moment of inertia are generated by pre-computation. (Requires trajectory planning.)	Lab

Complete real-time dynamic correction.	Experimental
Two handed cooperative manipulation.	Experimental

Trajectory planner

Playback of trained motion.	Factory
Joint space trajectory planner.	Factory
Coordinated joint motions in Cartesian or joint space. Smooth start and finish with via-points. Off-line computation.	Lab
Real-time coordinated joint trajectories with position/velocity via points.	Experimental
Energy minimizing trajectories	0,?

Obstacle avoidance

Trajectories hand picked to avoid obstacles.	Factory
Simple UP-OVER-DOWN strategy for avoidance.	Lab
Crude models of obstacles permit prediction of collisions. Alternative trajectory is not found.	Lab
Detailed object models predict collisions.	Experimental, -
Use models with real-time trajectories.	0, -
Sensors detect impending collisions.	0

Controller Architectures

Analog servos.	Factory
Digital servos	Factory
Hybrid digital+analog controller.	0
Microprocessor per joint controller.	Lab, +
Microprocessor per function controller.	Experimental
Very special purpose hardware	0

SENSING

Force

Forces at hand are determined from motor currents.	Lab
Forces are detected in fingers.	Lab
Three forces and three torques are measured at the wrist.	Lab
Forces and torques measured in work station.	Lab

Touch

Micro-switches in the fingers detect an object.	Factory

Touch sensor array gives information about location and pattern of touch.	Lab

Proximity

Ultrasonic sensor detects object between fingers. (Not usable in space.)	Lab
Optical sensor mounts on fingers.	Lab

Computer vision

- camera arrangements

Single fixed camera	Factory
Computer controlled pan and tilt	Laboratory
Computer controlled iris and focus	Experimental
Stereo pair of cameras	Lab
Orthogonal set of 2 or more cameras	0

- raw data type

Binary images	Factory
Grey level images (16, 64, or 256 levels)	Factory
Color data	Experimental
Time-of-flight laser range data	Lab
Triangulation laser range data	Lab

- object recognition and description

Two-dimensional scenes	Factory
Three-dimensional scenes	Lab
Detect identity position, and orientation of known objects when presented in isolation against simple background with controlled lighting	Factory
Precisely determine position and orientation of known object when presented against complicated, but known background, with some control over lighting	Experimental
Clusters of different objects	Lab
Shadows (special cases)	Lab
Track motion of part	Lab
Locate special label in cluttered scene	Experimental
Track moving label	Lab, Experimental

- manipulator control

Automatic calibration of relationship between manipulator and camera position	Lab
LOOK-COMPUTE-MOVE strategy used for 2-D visually controlled manipulator	Factory

LOOK-COMPUTE-MOVE strategy used for 3-D visually controlled manipulator	Lab
Pseudo real-time (0.5 - 1.0 sec per cycle) 2-D visually controlled manipulator	Lab
Real-time 3-D visual control of manipulator with special markings	Experimental

- computation

Dedicated mini- or micro-computer	Factory
Large general purpose computer	Lab
Array processing + general purpose computer	Lab
Hardware feature extraction at video rates	Lab

MECHANICAL CONSIDERATIONS -- GRIPPERS AND FIXTURES

Grippers

Two finger grippers	Factory
Interchangeable, special purpose grippers	Lab
Three finger gripper	Experimental
General purpose gripper	-
Advanced automated special purpose tools. These "hand" held devices must incorporate sensors, computation, and actuators	0

Fixturing (A well understood technology)	Factory

NASA-JPL-Coml., L.A., Calif.